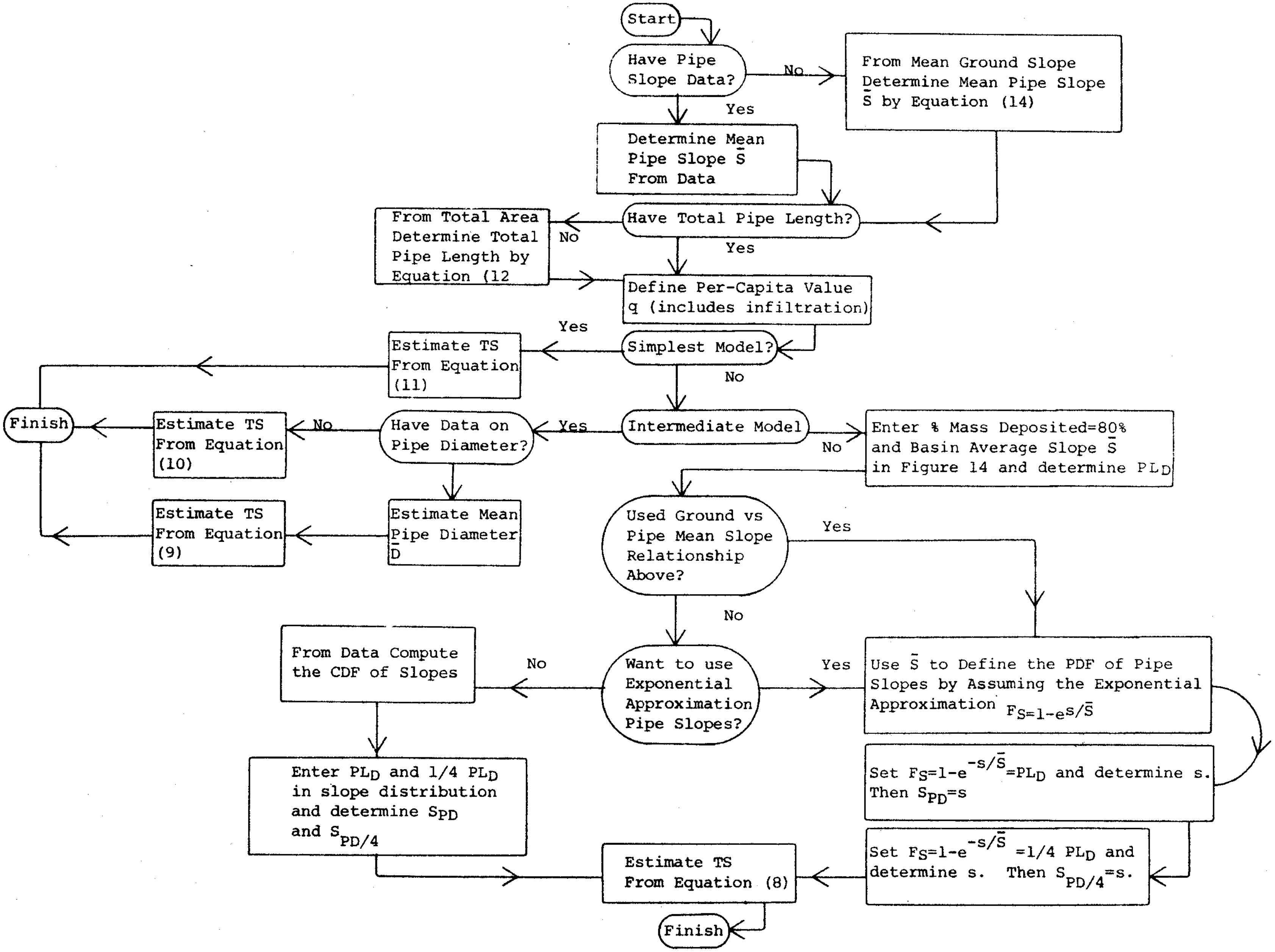

FIGURE 15. USER STEPS TO DETERMINE SOLIDS DEPOSITED-TS

to determine S_{PD} and $S_{PD/4}$ as described in Section 5.2.5.2. Finally, the user can define the pipe slope CDF from the pipe slope data and derive from it, the values of S_{PD} and $S_{PD/4}$ as described in Section 5.2.5.2. Finally, the user can define the pipe slope CDF from the pipe slope data and derive from it, the values of S_{PD} and $S_{PD/4}$ corresponding to the percentages PL_D and $1/4PL_D$, respectively. At this point all the elements are prepared to estimate TS from equation (8) which provides the most reliable estimate of TS.

The resulting estimate of TS is the total daily solids deposition in the collection system of interest. If the user wishes to modify this estimate for pipes with existing sediment beds the multiplicative equations in Section 4.5.4 should be used. If estimates of other pollutants are desired, the deposited solids results, TS, should then be used as predictors to compute other pollutant estimates using the equations given in Section 4.5.5.

5.3.2 Application of Procedures

In this section an example problem illustrating the methodologies developed in this report is presented. The test case is one of the collection systems in the Dorchester sewerage system. Estimates of total daily solids deposition in this collection system will be given for different assumptions of data availability using the simplified procedures. These estimates will also be compared with the results computed for this system using the much more detailed procedure described in Appendix B.

The test case used is basin number 70 of the Dorchester combined sewer system. There are 190 manhole segments in this collection system. The topography of this combined sewer collection system is fairly hilly. The land use in the area is exclusively high density multi-family dwellings with a population density of 30 people/acre. The areal extent and total collection system pipe footgate is about one standard deviation above the mean of all the systems used in the regression analysis. The values of all the independent variables for basin 70 are given in Tables 5 and 8.

5.3.2.1 Data Requirements

The total pipe length, L, for the basin is 35,033 feet and the total service area, A, is 233 acres. The total pipe length can also be computed using equation (12) for high population density yielding 37,740 feet, representing an overestimation error of 7.7 percent.

There are three possible ways to compute the values of the pipe slope variables required as input for the various regression equations. The first method involves computing these parameters from the distribution derived from actual pipe slope data. The second procedure requires knowledge of only the mean collection system pipe slope, $\bar{S}$, and assuming that the pipe slopes can be represented by an exponential distribution. The third alternative approach assumes that only ground slope information is available and that the exponential distribution is applicable to represent collection system pipe slopes.

The collection system pipe slope histogram representing the distribution of 190 pipe segments in basin 70 of the Dorchester sewerage system is given in Table 16. This table was prepared using the invert elevations for each of the 190 segments. The pipe slope histogram is divided into 30 intervals with the upper pipe slope limit of each interval given. The elements under the column labeled "frequency" are the actual pipe footages associated with each pipe slope interval. The last two columns give the interval probability computed using the pipe footage per interval relative to total pipe footage and the cumulative probability. The mean and standard deviation are also given in Table 16. The average equivalent circular diameter, $\bar{D}$, is 15.6 inches and was computed using the formulas given in Table 7, page 33 and equation (16).

The average pipe slope, $\bar{S}$, is 0.0194. The slope parameter S_{PD} can be estimated in the following manner. Three curves are available in Figure 14, page 38, for relating the cumulative distribution of solids deposited to cumulative distribution of collection system pipe length. Curve 2 is applicable in this case since the average pipe slope is 0.0194. The percentage of pipe associated with 80 percent of the total daily load deposited is 38%.* The value of the variable, S_{PD}, can then be determined by entering 0.38 in the last columun of Table 16 and interpolating the corresponding value of slope in column two. The interpolated value of S_{PD} is 0.00629. The value of $S_{PD/4}$ is obtained by entering the same table with 0.38/4 = 0.095, yielding $S_{PD/4}$ = 0.00302.

In the second procedure the mean pipe slope can be used in the exponential cumulative distribution function given by equation (1), page 22, to compute the values of S_{PD} and $S_{PD/4}$. The value of S_{PD} is 0.00928 results from using FS = 0.38, s = S_{PD} and $\bar{S}$ = 0.0194 in equation (1). The value of $S_{PD/4}$ is 0.00194 results from setting FS = 0.38/4 = .095 in equation (1).

---

* The distribution of loads by pipe length derived for basin 70 yields exactly 38% at 80% of the total load. The error involved in using Figure 14 is zero in this example.

TABLE 16. DISTRIBUTION OF PIPE SLOPES FOR BASIN 70

AVG. DIAMETER = 15.6

HISTOGRAM FOR FIXED RANGES (MAX. AND MIN. ABCISSA VALUES SPECIFIED)

INTERVAL	UPPER LIMIT OF RANGE	FREQUENCY	PROBABILITY	CUMMULATIVE PROBABILITY
1	0.000100	0	0.0	0.0
2	0.003311	3680	0.1045	0.1045
3	0.006521	10477	0.2974	0.4019
4	0.009732	3239	0.0920	0.4938
5	0.012943	4099	0.1164	0.6102
6	0.016154	1189	0.0338	0.6440
7	0.019364	680	0.0193	0.6633
8	0.022575	832	0.0236	0.6869
9	0.025786	1229	0.0349	0.7218
10	0.028996	752	0.0213	0.7431
11	0.032207	472	0.0134	0.7565
12	0.035418	909	0.0258	0.7823
13	0.038629	1485	0.0422	0.8245
14	0.041839	371	0.0105	0.8350
15	0.045050	752	0.0213	0.8564
16	0.048261	247	0.0070	0.8634
17	0.051471	315	0.0089	0.8723
18	0.054682	460	0.0131	0.8854
19	0.057893	1528	0.0434	0.9288
20	0.061104	0	0.0	0.9288
21	0.064314	560	0.0159	0.9447
22	0.067525	68	0.0019	0.9466
23	0.070736	1033	0.0293	0.9759
24	0.073946	334	0.0095	0.9854
25	0.077157	16	0.0005	0.9858
26	0.080368	0	0.0	0.9858
27	0.083578	340	0.0097	0.9955
28	0.086789	126	0.0036	0.9991
29	0.090000	0	0.0	0.9991
30	> 0.090000	32	0.0009	1.0000

Mean = .0194058 Standard Deviation = .020859

The only information required for the third procedure is the average ground slope, $\bar{S}_G$. The average ground slope for basin 70 was determined by graphical procedures to be 0.0359. An estimate of the mean pipe slope, $\bar{S}$, can be obtained using the mean ground slope in equation (14). The estimated value of mean pipe slope, $\bar{S}$, using the mean ground slope, $\bar{S}_G$, is 0.02287 differing from the actual mean pipe slope by 17%. Values of S_{PD} and $S_{PD/4}$ can now be estimated using the exponential relationship in equation (1), yielding S_{PD} = 0.00985 and $S_{PD/4}$ = 0.00228.

5.3.2.2 Estimation of Loads

The detailed manhole to manhole dry weather deposition model described in Appendix B was used to estimate total solids deposited for the entire collection system network in basin number 70. The estimated load is 169.11 lbs/day using an average per capita waste rate of 190 gpcd. This model requires detailed specification of the hydraulic parameters for each segment in the system and the use of a computer. Similar estimates will be computed from using the simplified power functions generated in this study for the three different estimates of the pipe slope variables.

The elaborate model given in equation (8) requires specification of L, S_{PD}, $S_{PD/4}$ and the per capita flow rate, q. This equation was solved for the three different estimates of S_{PD} and $S_{PD/4}$ with q = 190 gpcd. The deposited load, TS, is 155.73 lbs/day using the values of S_{PD} and $S_{PD/4}$ derived from the analysis of detailed collection system pipe slope information. The estimated load is 118.72 lbs/day using values of S_{PD} and $S_{PD/4}$ computed from the mean pipe slope and the exponential cumulative function. The estimated load is 111.11 lbs/day using values of S_{PD} and $S_{PD/4}$ for the third situation where the mean ground slope is used to compute mean pipe slope for input into the exponential function.

The intermediate model given by equation (10) requires that L, A, $\bar{S}$, and q be specified. Three variations are computed using this formulation. The first estimate is determined using the measured pipe length, L and pipe slope, $\bar{S}$, derived from data; the second case uses the measured pipe length and an estimate of mean pipe slope from ground slope estimate; and the third result is computed using the estimated pipe slope, $\bar{S}$, and an estimate of pipe length derived from equation (12). These three estimates are 186.89, 174.02 and 190.55 lbs/day, respectively.

The simplest model given by equation (11) requires specification of L, $\bar{S}$ and q. The estimated loads are 198.82 lbs/day using exact estimates of L and $\bar{S}$, 195.02 lbs/day using exact estimates of pipe length and an estimate of pipe slope ground ground slope, and, 200.26 lbs/day using estimated values of both pipe length and mean pipe slope.

A comparison of all computed loadings for the different predictive models under different assumptions of data availability is given in Table 17. The percentage error relative to the estimate provided by the procedure in Appendix B is also provided. These results show that the estimated values given by all three regression equations are reasonably close to the value derived from the detailed model described in Appendix B. The elaborate model consistently gave over estimates.

It is an invalid conclusion to infer from this comparison that the simpler approach might be superior to the more elaborate one. It should be noted that this comparative result is only for one basin and that on the average, the elaborate model will provide consistently superior results because the coefficient of determination R^2, is higher for the elaborate model. The under estimates given by the elaborate model using approximations for the pipe slopes are explained by the fact that, for this particular basin, the exponential approximation over estimated by about 50% the slope, S_{PD}. Nevertheless, one of the simpler models would be more appropriate in cases where little data is available requiring many assumptions and approximations. Moreover, the utilization of the simpler models for planning "first-cut" purposes may be more cost effective from the standpoint of collecting, analyzing and preparing the required data inputs.

In sum the simplified procedures given by equations (8), (10) and (11) provide estimates of daily solids deposition using exact data for basin 70 with a relative error of 8 to 18 percent in comparison to the estimate given by the complicated procedure described in Appendix B. It is shown in Appendix C of this report that the complicated procedure given in Appendix B was tentatively calibrated using actual field flush information lending credulence to the adoption of the simplified procedures generated in this report.

TABLE 17. COMPARISON OF ESTIMATED DAILY SOLIDS DEPOSITED FOR BASIN 70 USING DIFFERENT PROCEDURES

Procedure	Solids Deposited (lbs/day)	Percentage Error Relative to Appendix B Results
Deposition Model (Appen. B)	169.11	
Elaborate Model (Eq. (8))		
Exact Data	155.73	-7.9%
Exponential Data	118.72	-30.0%
SG and Exponential Approx.	111.11	-34.0%
Intermediate Model (Eq. (10))		
Exact Data	186.89	+10.5%
Estimated Slope $\bar{S}$	174.02	+3.0%
Estimated L and $\bar{S}$	190.55	+12.7%
Simplest Model (Eq. (11))		
Exact Data	178.82	+17.6%
Estimated $\bar{S}$	185.03	+9.4%
Estimated L and $\bar{S}$	200.26	+18.4%

5.3.3 Determination of Deposition Extent in Collection Systems

Estimates of total pipe footage for given percentages of the total solids deposition can be made using Figure 14. These estimates are computed irrespective of their actual location in the collection system. The appropriate curve in Figure 14 can be chosen. Using the average pipe slope $\bar{S}$ as a guide, several values of "% pipe length" can be read directly from the figure as a function of values of "% mass deposited". Multiplication of the total basin pipe length by those percentages yields estimates of pipe footage corresponding to the various percentages of total solids deposited. Those estimates can be used in preliminary assessments of costs associated with pipe cleaning by mechanical or flushing techniques to achieve different levels of total deposited mass removals.

It should be noted that the estimates of total pipe footage corresponding to given levels of deposition do not define where in the system those pipes lie. With one simple assumption, the locations in the system of the deposited pipes can be tentatively established. This assumption can be understood considering Figure 16. In part a of Figure 16, an estimate of the percentage of the total pipe length PL over which a percentage of the total mass of solids, PM, deposits is shown. The percentage of total pipe length in the basin with pipe slope smaller than or equal to S_{PL} is shown in part b of Figure 16. Combining the two parts in Figure 16, does not necessarily mean that the pipes over which PM deposits all have slopes flatter than or equal to S_{PL}. This may be a reasonable working assumption and, if it is made, locations of depositing segments can be determined. This step can be accomplished by noting on a sewerage system map all pipe segments with slopes equal to or smaller than S_{PL}. This procedure will quantify the sewer segments associated with the percentage PM of the total load. A check of the approach can be made be measuring those pipe lengths and comparing their sum with the estimate given by $L_{PM} = PL \times L$

where: L_{PM} = estimated length over which the percentage PM of the total mass deposits;

PL = the corresponding percentage of pipe length (from Figure 14); and

L = total length of pipe in the basin.

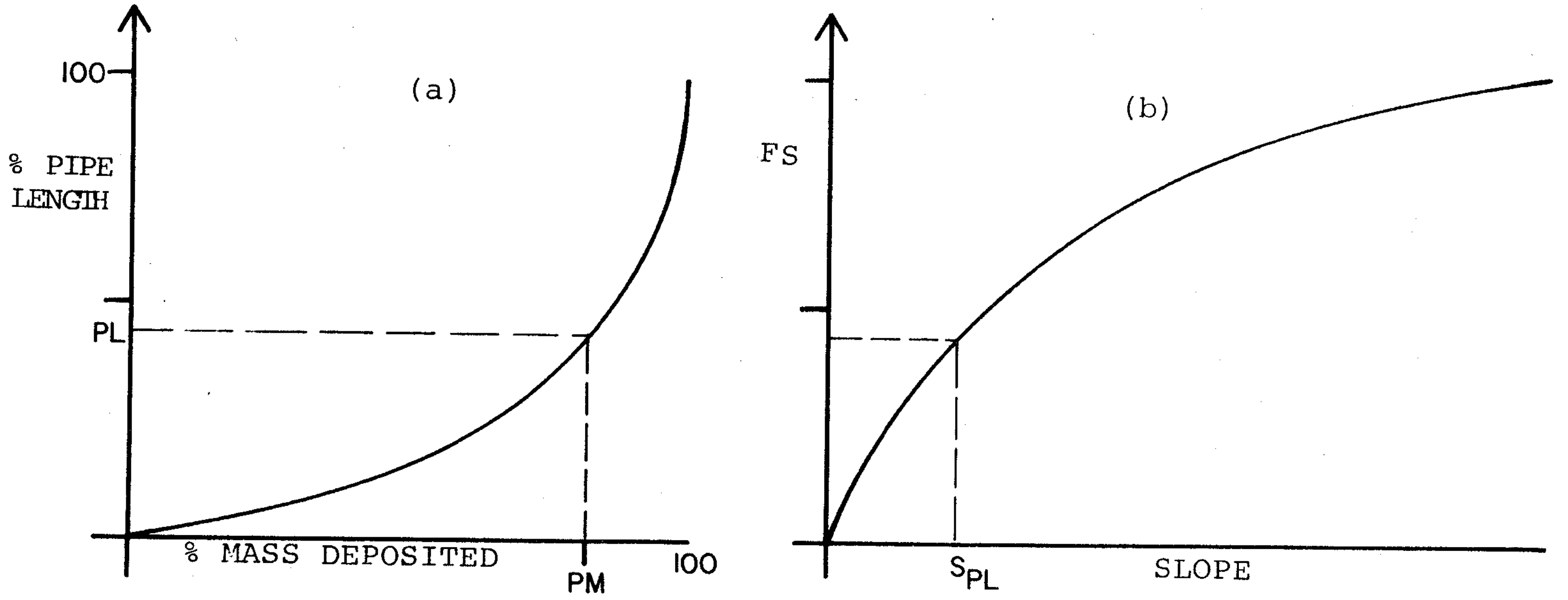

FIGURE 16: DETERMINATION OF THE CUT-OFF SLOPE FOR A PERCENTAGE OF MASS DEPOSITED

REFERENCES

1. FMC Corp., "A Flushing System for Combined Sewer Cleansing," U.S. EPA Report 11020 DNo, March, 1972.

2. Process Research, Inc., "A Study of Pollution Control Alternatives for Dorchester Bay," Metropolitan District Commission, December, 1976.

3. "Design and Construction of Sanitary and Storm Sewers". Prepared by a joint committee of the American Society of Civil Engineers and the Water Pollution Control Federation (1969).

4. Yao, K.M., "Sewer Line Design on Critical Shear Stress," Journal Environmental Engineering Div., (ASCE) 100: E22, April, 1974.

5. Camp, T.R., "Design of Sewers to Facilitate Flow," Sewage Works Journal, 18:3 (Jan. 1946).

6. "Minimum Velocities for Sewers", Final Report of Committee to Study Limiting Velocities of Flow in Sewers, Boston Society of Civil Engineers, 29:4 (October, 1942).

7. Raths, C.H., McCauley, R.F., "Deposition in a Sanitary Sewer", W&SW, No. 1962, pp 238-243.

8. Metcalf & Eddy, Inc., "University of Florida, Water Resources Engineers, Inc., "Storm Water Management Model", EPA (July, 1971).

9. Fair, G.M., Geyer, J.C., Okun, D.A., Water and Wastewater Engineering, Vol. 1: WAter Supply and Wastewater Removal (1966).

10. Hughmark, G.A., "Aqueous Transport of Settling Slurries", Industrial and Engineering Chemistry, Vol. 53 (May 1961).

11. FMC Corp., "Relationship of Sewage Characteristics to Carrying Velocity for Pressure Sewer", August, 1969, American Society of Civil Engineering, No. R-2598.

APPENDIX A

BRIEF REVIEW OF R&D SEWER FLUSHING PROJECT

A brief review of the R&D sewer flushing program objectives and project scope will be presented in this appendix. Next a summary review of the pollutant removals resulting from manual flushing of four test segments during the first phase of the program will then be provided.

Conceptual Views of Program

The solids control demonstration/research program has been developed to address many of the issues relating to the feasibility, cost-effectiveness, and ease of application of upstream solids control program as an integral part of overall combined sewer management. Basically, there are five fundamental issues that must be answered before widespread acceptance of upstream solids control may be considered. The issues include: 1) what are the best flushing methods to use for a given situation; 2) what is the expected pollutant removal efficiency associated with the various methods; 3) what are the costs associated with such programs; 4) how do you screen large systems to identify problem pipes with respect to deposition and; 5) what are the effects of stormwater runoff on such a strategy as applied to combined sewer systems.

Program Objectives

1. Test the feasibility of applying various solids control techniques as a method of deposition control in combined and sanitary sewer lines on test segments in the Boston sewer system.

2. Carefully monitor deposition rates on a number of test segments.

3. Monitor pollutant removals including solids, organics and nutrients associated with the various solids control techniques.

4. Assess pollution oriented characteristics of both the flushed and remaining materials versus maintenance problems of grit, sand and gravel accumulations.

5. Recommend most favorable solids control techniques for operational testing by both automated and manual means.

6. Develop, test and evaluate automated control systems in a field operational testing program.

7. Develop, test and evaluate manual sewer flushing techniques utilizing specially equipped water tankers in a field operational testing program.

8. Assess the operational feasibility and performance of flushing both long and short upstream collection segments and/or networks.

9. Assess the effects of stormwater washoff on the characterization of combined sewer solids.

10. Refine existing deposition model and flushing criteria.

11. Compare solids control vs selected structural options as a combined sewer abatement technique.

12. Develop user guideline for solids control program as an integral part of sewer management schemes.

Figure A-1 is an overview schematic of the program. The program is broken into three distinct phases: 1) a field feasibility analysis of various solids control (flushing) techniques to test the feasibility of applying various techniques to actual sewer lines; 2) an operational testing program to assess the operational feasibility of applying optimum strategies to sewer systems; and 3) a detailed data analysis and costing phase to develop a reasonable deposition model and flushing criteria, and analyze the concept of upstream solids control as an integral part of combined sewer abatement schemes.

The feasibility analysis is aimed at answering the question of what are typical deposition rates in sewerage collection systems, what are the best flushing techniques to use, and what pollutant reductions can be reasonably expected as well as supplying a wealth of data for the refinement of the existing deposition model and flushing criteria. The operational testing program will take the optimum strategies developed in the feasibility analysis and put them into an actual 10 week program aimed at continuing data development as well as testing the operational feasibility of such a program by both manual and automated means.

From the large data base developed during the two field programs, a refined practical deposition model and flushing criteria will be generated. These refined formalisms will allow for scanning of large-scale sewer systems to identify problem pipes with respect to deposition. The refined tools will allow for

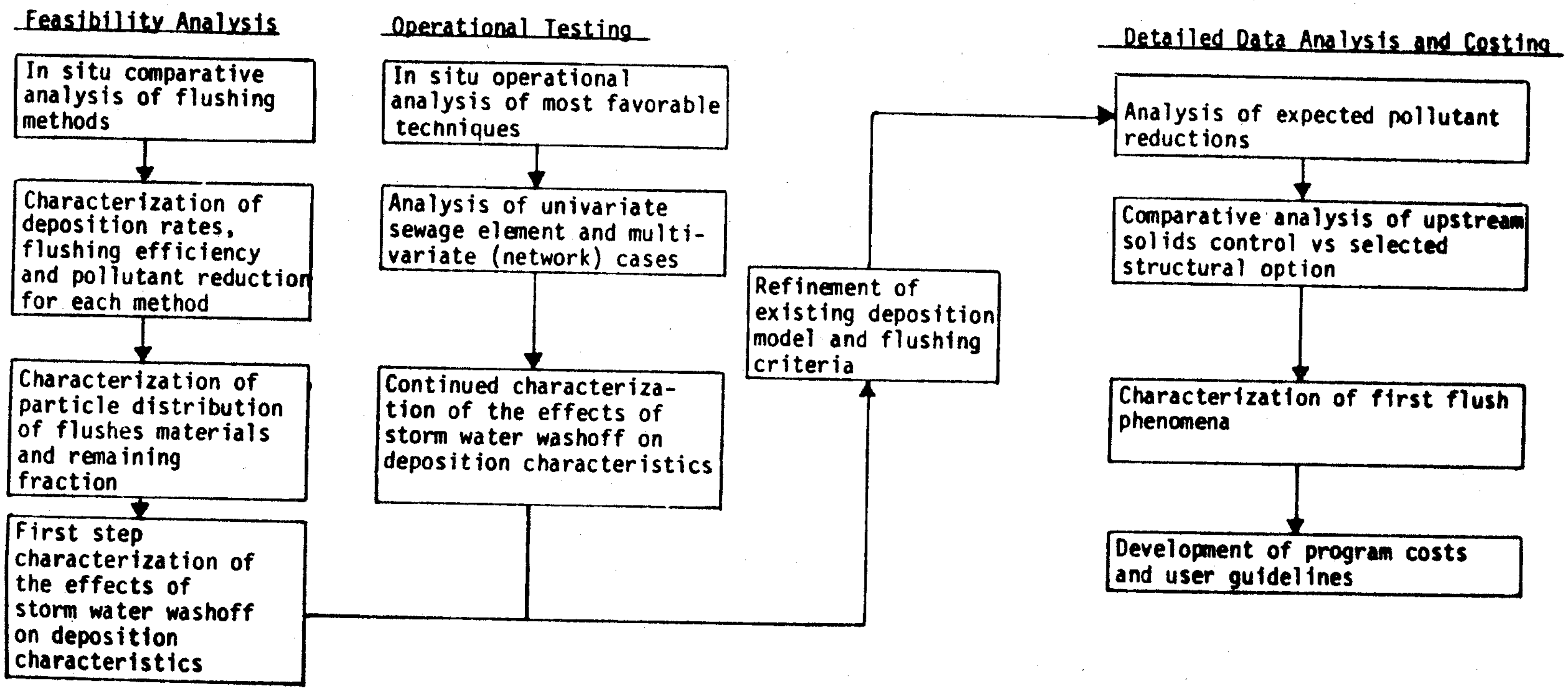

FIGURE A-1. SCHEMATIC OVERVIEW OF PROGRAM comparative analysis of upstream solids control vs selected structural options to compare program efficiencies. The tools will also allow for rough assessment of first flush phenomena as related to combined sewer systems to better clarify the questions over the use of upstreams "first-flush" collection devices. Finally, the program will develop data to generate a set of engineering user guidelines to apply the deposition analysis to large-scale systems.

Results of First-Phase Feasibility Flushing Programs

After a careful review and inspection program, four streets were selected for the flushing experiments. These streets are all in Dorchester characterized by high density, 3-story multi-family dwellings. Two of the test segments located on Port Norfolk and Walnut Street are served by flat combined sewer laterals of 12" and 15" circular pipe, respectively. The total tributary population down to and including the test segments are 94 and 71 people, respectively. The other two test segments on Shepton and Templeton Streets, are serviced by separate sewer laterals of 12" and 15" circular pipe, respectively. There are downspouts on both streets connected to the sanitary sewer. The total tributary population for these two streets are 224 and 221, respectively. The pipe slopes of the test segments range from 0.003 to 0.004. The flushing program in this phase is concerned only with the effects of flushing a single manhole to manhole segment. Three different methods of manual flushing were performed. The first method consisted of backing up the upper end of the flushing manhole with an inflatible rubber stopper with quick release. The other two methods were gravity and pressurized dump discharge into the flush manhole with the upper end of the flush manhole blocked off. These flushes were performed using a specially designed water tanker with two 1000 gallon tanks mounted on a steel I-beam skid. The tanker was equipped with a pneumatic system to pressuirze the tanks to 30 psi. The operation under gravity conditions provided a controlled flush release of 35 to 50 cubic feet at a rate of 0.25 to 0.50 cfs. Under pressurized conditions the same volumetric range of flush was accomplished at a rate of 0.5 to 1.25 cfs. Sixteen to eighteen grab samples of flush wave were taken at 10 second intervals for the first 80 seconds after the flush wave reached the downstream manhole and then at 20 second intervals. Wave heights were taken at each interval of time which were later used to determine the instantaneous flow rate for computing mass pollutants removed by the flushing experiment.

The total pollutant mass removals in kilograms, for each of the four test segments are given in Table A-1. This data is preliminary and is subject to change pending further field refinment of stage/discharge rating procedures used to convert flush wave heights to discharge quantities. The mean and standard deviation of the pollutant mass removals in kilograms for each of the four test segments is given in Table A-2. The mean and standard deviation of the pollutant mass removals normalized for the number of antecedent days between flushing experiments is provided in Table A-3. These statistics are computed for all experiments including those impacted by rainfall events occurring between the flushing experiments. Statistics for subsets of this data excluding the rainfall impacted experiments are presented in Appendix C. The data used in the regression analysis presented in Table 15 of Section 4.5.4 was prepared by normalizing the raw results given in Table A-1 and then converting the results into lbs/day.*

---

* It is assumed in the regression analysis cited in Section 4.5.4 that the normalized pollutant loads removed by flushing equals the daily deposition rate. Preliminary results of the second phase of field flushing indicates flushing removal effectiveness ranging from 75 to 90 percent. These results will be used during a later phase in this project to reexamine the results given in Section 4.5.4

TABLE A-1. TOTAL MASS OF POLLUTANT REMOVED BY FLUSH

Location: Port Norfolk Street

	TOTAL MASS (kg)						
DATE	COD	BOD	TKN	NH_3	P	TSS	VSS
8/30/76	1.54	0.81	0.04	0.01	0.02	3.94	1.24
9/2						12.37	7.58
9/7	5.49	2.92	0.25	0.05	0.05	16.04	11.02
9/16						2.90	1.96
9/21	4.60	0.78	0.22	0.04	0.06	6.50	3.14
9/24						5.74	3.67
10/1	9.37	3.40	0.33	0.04	0.04	11.36	9.35
10/4	7.49	2.90	0.28	0.06	0.06	7.10	5.42
10/8						2.97	1.92
10/12	4.51	1.61	0.16	0.02	0.04	5.81	4.27
10/15						2.73	2.16
10/18	5.68	2.00	0.16	0.03	0.001	4.90	4.03
10/25						1.52	1.11
10/22						2.36	1.79
10/29						3.04	2.49
11/1	3.71	1.17	0.12	0.03	0.02	2.94	2.30
11/5						2.23	2.04
11/8	3.36	1.42	0.10	0.03	0.03	3.32	2.57
11/12		3.30				4.79	4.47

continued

TABLE A-1 (continued)

Location: Templeton Street

	TOTAL MASS (kg)						
	COD	BOD	TKN	NH_3	P	TSS	VSS
8/30						10.84	4.01
9/2		2.96				7.68	4.93
9/7						1.19	1.01
9/10		3.66				8.51	6.52
9/13	2.54	0.45	0.07	0.01	0.01	2.26	1.70
9/16		0.08				0.23	0.16
9/21						1.88	1.10
9/24						0.32	0.27
10/1						5.13	3.60
10/4						2.70	2.19
10/8		1.50				6.89	5.95
10/12						13.06	10.49
10/15		0.96				4.97	3.45
10/18						13.95	11.09
10/22		3.92				5.06	3.32
10/25						4.40	3.58
10/29		4.41				10.04	7.44
11/1						4.70	3.23
11/5		5.25				12.74	10.52
11/8						5.38	3.96
11/12		3.80				-	-

continued

TABLE A-1 (continued)

Location: Shepton Street

	TOTAL MASS (kg)						
	COD	BOD	TKN	NH3	P	TSS	VSS
8/23	5.63	1.21	0.09	0.03	0.03	3.91	2.81
8/30						2.84	1.71
9/2		1.75				5.70	4.17
9/7						14.11	11.04
9/10		1.58				5.71	4.58
9/13						2.42	1.93
9/16		1.89				5.67	4.46
9/21						4.27	2.83
9/24		0.65				2.57	1.87
10/1						3.34	2.31
10/4						5.76	4.71
10/8		2.31				6.09	4.84
10/12						4.32	3.12
10/15		2.64				4.82	3.87
10/18						6.54	5.24
10/22		1.38				2.93	2.31
10/25	8.00	2.09	0.20	0.04	0.05	4.53	3.83
10/29		0.99				3.51	2.86
11/1						3.60	2.93
11/5		2.35				5.49	4.55
11/8						5.51	4.37
11/12						1.03	0.89

continued

TABLE A-1 (continued)

Location: Walnut Street

TOTAL MASS (kg)

	COD	BOD	TKN	NH_3	P	TSS	VSS
8/23	3.5	0.83	0.07	0.04	0.03	2.74	1.17
8/26		1.18				0.52	0.22
8/30	12.44	1.29	0.35	0.1	0.07	14.94	7.72
9/2						1.76	0.90
9/7	0.66	0.22	0.03	0.02	0.01	0.63	0.27
9/10						0.98	0.87
9/13	3.06	0.61	0.08	0.07	0.02	14.23	8.25
9/16						0.46	0.37
9/21	1.36	0.24	0.03	0.01	0.02	2.75	0.78
10/1	3.37	1.26	0.10	0.02	0.04	2.83	1.91
10/4	1.15	0.45	0.05	0.01	0.01	1.21	0.84
10/12	13.70	3.61	0.25	0.05	0.04	14.32	8.13
10/15						0.57	0.30
10/18	1.21	0.57	0.07	0.03	0.0005	1.08	0.82
10/22						4.24	4.17
10/25	2.12	0.52	0.07	0.03	0.02	1.53	0.87
10/29						1.34	1.00
11/1	1.67	0.70	0.06	0.02	0.01	1.01	0.74
11/5						3.33	2.39
11/8	4.25	1.67	0.11	0.06	0.02	3.34	2.18
11/12						0.48	0.48

TABLE A-2. STATISTICS OF POLLUTANT MASS REMOVALS (kg) RAW DATA

STREET	STATISTICS	COD	BOD	TKN	NH_3	P	TSS	VSS
Port Norfolk	Mean	5.08	2.03	0.18	0.03	0.04	5.39	3.82
	St. Deviation	2.31	1.02	0.09	0.02	0.02	3.90	2.76
Shepton	Mean	6.82	1.71	0.145	0.035	0.04	4.76	3.69
	St. Deviation	1.68	0.62	0.078	0.007	0.01	2.53	2.03
Templeton	Mean	2.54	2.70	0.07	0.01	0.01	6.10	4.43
	St. Deviation	-	1.81	-	-	-	4.27	3.33
Walnut	Mean	4.04	1.01	0.11	0.04	0.024	3.54	2.11
	St. Deviation	4.37	0.90	0.10	0.03	0.019	4.71	2.64

\- Too few data points to compute standard deviation.

TABLE A-3. STATISTICS OF POLLUTANT MASS REMOVALS (kg/ANTECEDENT DAY) DATA NORMALIZED FOR ANTECEDENT DAYS

STREET	STATISTICS	COD	BOD	TKN	NH_3	P	TSS	VSS
Port Norfolk	Mean	1.41	0.55	0.05	0.01	0.01	1.49	1.03
	St. Deviation	0.53	0.25	0.02	0.04	0.005	1.04	0.64
Shepton	Mean	1.89	0.50	0.05	0.01	0.02	1.36	1.06
	St. Deviation	1.09	0.21	0.04	*	0.01	0.63	0.52
Templeton	Mean	0.85	0.81	0.02	0.002	0.003	1.66	1.25
	St. Deviation	-	0.54	-	-	-	1.17	0.92
Walnut	Mean	0.95	0.25	0.027	0.010	0.006	0.90	0.54
	St. Deviation	0.83	0.15	0.021	0.008	0.004	1.19	0.67

- Too few data points to compute standard deviation
* Smaller than 0.0001

APPENDIX B

DISCUSSION OF SIMPLIFIED SEWER SYSTEM DEPOSITION MODEL

The details of a procedure for obtaining quick and inexpensive estimates of the amount of daily dry weather deposition loadings within each manhole to manhole segment of a sewer collection system are provided in this appendix. A number of crude approximations and simplifications are used in this procedure and therefore, the results are not purported to be a substitute for those provided by more rigorous approaches.

One distinct advantage of this model is that it is devised to consider each element of an entire collection system network. It is intended to provide estimates for only dry weather conditions and has no provisions for considering transient wet weather phenomena. No distinction is made between bedload, suspended load and washload deposition and resuspension characteristics. The major simplifying assumption of the model is that the amount of deposition remaining in any segment over the course of a day is computed as the residual loadings not washed or moved downstream during peak dry weather flow conditions. No detailed accounting is made of the temporal pattern of diurnal deposition, resuspension and transport phenomena. The basic structure of the model was developed during a prior combined sewer management study (2). In a latter phase of this R&D sewer flushing project the data obtained from the field flushing program will be used to further refine formalisms presented in this appendix.

General Concepts

A well designed sewerage system should not only convey flows but should also minimize the deposition of sewage solids during dry weather conditions. There are in use an ample number of suitable empirical and theoretical equations for flow design but no uniform criteria have been established to prevent solids depostion.

The approach commonly used to prevent deposition is the method of minimum permissible velocity (3). However, the use of average velocity consideration is not necessarily the most robust criterion to use for a wide range of typical operating conditions.

A more fundamental approach is the method of critical shear stress, τ, given by equation (1).

$$\tau = \rho r s s \quad (1)$$

where ρ = specific weight of water

r = hydraulic radius, and

ss = energy slope

Yao (4) reviewed experimental results dealing with fluid shear stress measurements and concluded that the average boundary shear stress computed by equation (1) will approximate the actual local boundary shear stress within the possible region of deposition, provided that the flow depth is equal to or greater than one-third of the sewer diameter.*

Yao also included that a shear stress of .02 or .04 psf is adequate for self-cleaning sanitary sewers, while a shear stress of .06 to .08 psf is necessary to dislodge heavy sand and gravel, and is required for self-cleaning of combined systems. In addition, this work showed that the present practice of using a constant minimum velocity for all sewer sizes tends to under-design larger sewers and over design smaller sewers.

Deposition Mechanisms

Shield's classic results are commonly used to predict solids deposition in sewerage systems. Shield's results, however, relate to bedload movement and specifically to uniform particles moving on the surface of the bed. In simple terms, there are two primary mechanisms involved in the transport of sewage particles: bedload transport and suspension.

The first to used bedload transport considerations to predict deposition was Camp (5,6,) and others have since used this technique (7,8,9). Shield's relationship** for bedload transport is given by:

$$\tau c = .020\ p \quad (2)$$

where p = particle diameter, (mm) and

τc = critical wall shear (psf)

* The actual or local boundary shear stress varies considerably, with the maximum occurring around the center line of the channel and the minimum near the water surface.

** Shield's constant equals 0.06 in this formulation.

The second transport mechanism is suspension. Hughmark (10) correlated 14 sets of data on slurry transport and Raths (7) conducted experiments on sand sediment in sewers. In order to prevent deposition of sand particles (specific gravity = 2.7), a critical wall shear must be maintained or exceeded. The results of their experiments can be summarized by the following relationship:

$$\tau c = .021\ p^{1/3} \tag{3}$$

The smaller particles (less than .05 mm) of Hughmark's data closely agree with the above functional form. A reasonable first order approximation is to assume that both mechanisms transport heterogenous materials through sewer systems. The geometric average of equations (2) and (3) can be used to predict transport requirements. The equation relating the critical wall stress, τc, necessary to move (and conversely to settle)* a particle of given diameter, p, is the following:

$$\tau c = .02\ p^{2/3} \tag{4}$$

Single Segment Deposition Model

Equation (4) and sewage particle size distributions can be used to predict the quantity of suspended solids deposited from dry-weather flow over a single length of pipe. The results computed from equation (4) with two particle distributions (11, 8) and the experimental results from the FMC study (1) were fitted by a simple single term power function given by equations (5) and (6):

$$Z = 40\left(\frac{\tau}{.004}\right)^{-1.2} \quad \text{for } \tau > .004 \text{ psf} \tag{5}$$

$$Z = 40 \quad \text{for } < .004 \text{ psf} \tag{6}$$

where Z is the percentage of the suspended solids in the dry weather sanitary flow that is deposited if the wall shear is less than τ.

The shear stress, τ, would be computed for maximum daily dry weather flow conditions. Maximum daily flow, Q_{MAX}, can be computed from average dry weather flow, Q_{AV}, using equation (7).

$$\frac{Q_{MAX}}{Q_{AV}} = a\ \overline{PP}^{b} \tag{7}$$

---

* Recent findings have shown that this assumption is erroneous, that is, a greater shear stress is required to move a particle of a given diameter than to permit settling. In a later phase of this project this assumption will be examined.

where PP is the contributing population in 1000's and a and b are determined from analysis of flow measurements. Typical values of the constant "a" range from 1.25 to 1.5 and a value of 1.47 was used in the computations described in Section 4. A value of 0.08 was used for the exponent "b". Both values were established from analysis of flow measurements.

Multi-Segment Models

In considering a series of sewer pipes having low values of fluid tractive shear, that is, characterized by low slopes or low flows (or both), the condition can arise where solids from an upstream reach can successively deposit in downstream pipes. The relative amounts deposited in any section would depend on the shear stress during peak flow in that link and also on the amounts deposited upstream. A general procedure is desired to predict the total cumulative load in any section from all upstream sources.

The procedure used is the following:

1. Segment the collection system into a network of "m" links where each link may be a section of pipe between manholes or several sections combined into a single section (similar hydraulic characteristics);

2. Establish, for all links, a list of all downstream sections that convey waste from the given link;

3. Compute cumulative upstream length of pipe at each link;

4. Compute average daily dry weather flow for each link using the cumulative length from step 3 and an average per capita waste rate;

5. Compute maximum daily dry-weather flow for each link using equation (7);

6. Compute shear stress for each link associated with the maximum daily flow, using equation (1) for the appropriate pipe shape;

7. Compute the dry-weather suspended solids deposition rates, $Z_i (i = 1,\ldots,m)$ from the shear stresses calculated in Step 6, using equations (5) and (6);

8. Compute the suspended solids load $ZL_i (i = 1,\ldots m)$ developed along each link using length of link, population per unit length and daily solids generated per capita;

9. Starting at the uppermost link, i, compute the amount of input material that will deposit, that is $Z_i \cdot ZL_i$;

10. Search the list of downstream links for the deposition rate, Z_j, greater than the rate at the link where the load is initially generated, and compute the amount deposited as the jth link from the ith component input load using $(Z_j - Z_i) \cdot ZL_i$;

11. Continue searching the list of downstream links for a deposition rate Z_k greater than Z_j and compute the deposition at the kth link from the ith component using $(Z_k - Z_j) \cdot ZL_i$;

12. Set $Z_k = Z_j$ and repeat Steps 10 and 11 until the complete list of downstream links is completed;

13. Start with the next uppermost link in the system and repeat Steps 9 through 12 while maintaining a running sum of all the deposited loads in each link from previous iterations; and

14. Sequentially proceed downstream until all components are completed.

In other words, a fraction of the load generated in an upstream section may deposit in that section (if the shear stress is sufficiently low) and more of that load may deposit in downstream sections only if the shear stress falls below levels experienced upstream.

The present model is coded to assume any collection system geometry with the one rule that only three segments can be considered at a given manhole. The model is coded to compute shear stress for circular, egg, ovoid, rectangular, horseshoe shaped cross-sections with and/or without pre-set sediment beds.

An idealized example using the schematic in Figure B-1 illustrates this procedure. Assume that the shear stress developed during peak dry-weather flow in links 1, 4, 5, 8 and 11 results in deposition rates of 10, 5, 5, 15 and 20 percent, respectively. Assume that the shear in all other links, i.e., 2, 3, 6, 7, 9 and 10, is sufficiently high to preclude any localized deposition. The dry weather load developed along each of the 11 links is, say, 100 units of dwf solids.

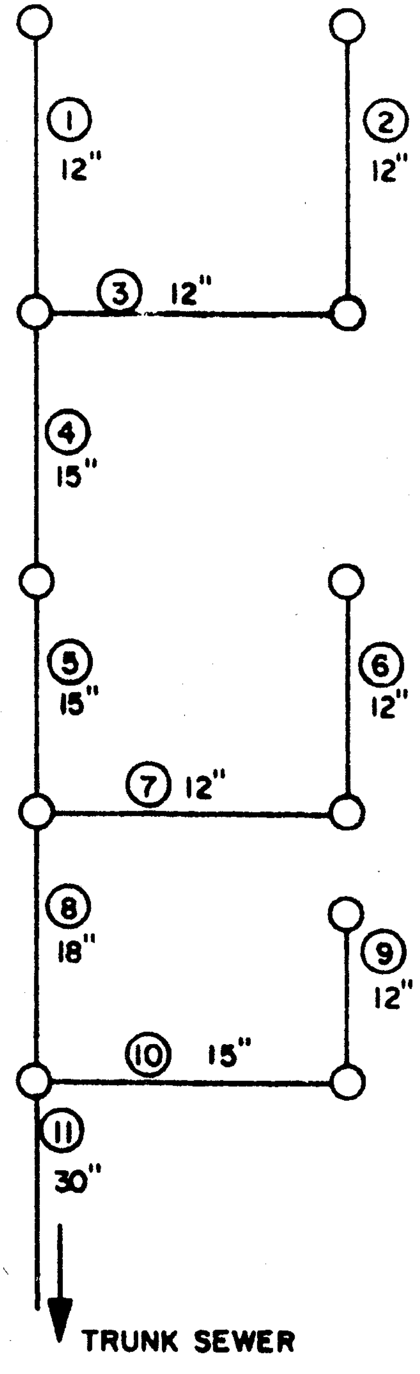

FIGURE B-1. SCHEMATIC OF COLLECTION SYSTEM

TABLE B-1. DEPOSITION ANALYSIS OF IDEALIZED SYSTEM

Link Numbers	1	2	3	4	5	6	7	8	9	10	11	Total Amount Deposited in Each Link
1	10.											10
2	-	0.										0.
3	-	0.	0.									0.
4	0.	5.	5.	5.								15.
5	0.	0.	0.	0.	5.							5.
6	-	-	-	-	-	0.						0.
7	-	-	-	-	-	0.	0.					0.
8	5.	10.	10.	10.	10.	15.	15.	15.				90.
9	-	-	-	-	-	-	-	-	0.			0.
10	-	-	-	-	-	-	-	-	0.	0.		0.
11	5.	5.	5.	5.	5.	5.	5.	5.	20.	20.	20.	100.

The ijth in the table represents the amount deposited in link i that originated in link j. Thus element (8,1) = 5 represents the amount deposited in link 8 that originated in link 1.

Table B-1 shows contributions from all upstream links on each downstream link and the total deposition in section 4 consists of loads from sections 2, 3, 4 but not from section 1 because the deposition rate, Z_1 is greater than Z_4. At link 5, the only amount deposited is from the load developed along that link (Z_1 is greater than Z_5: no deposits, Z_2 and Z_3 less than Z_5 but Z_4 equals Z_5: no deposits; Z_4 less than Z_5: deposits). The overall deposition rate for entire system is 20 percent (220 units deposited/1100 units total load) with nearly equal loadings in links 8 and 11.

APPENDIX C

PRELIMINARY DEPOSITION MODEL CALIBRATION RESULTS

In this appendix a preliminary verification is presented of the deposition model described in Appendix B using field flushing results derived from the data presented in Appendix A. The results presented here reflect no change in the model's internal relationships. It is envisioned that modifications will be made in a later phase of the study.

A comparison of field flushing results for four test segments with predicted deposition rates is presented in Table C-1. The contents of this table are described as follows: column (1) - test segment location; column (2) - average mass of suspended solids removed per flush normalized by the number of antecedent days between each of the flushes for all experimental data; column (3) - average mass of suspended solids removed per flush normalized by antecedent days for selected subset of the experimental results including only good experimental points free of rainfall events occurring between the flush periods; column (4) - predicted daily deposition rates over test segment for two per capita waste rates of 125 and 250 gallons per capita per day; column (5) - pipe size of test segment; column (6) - length of test segment; column (7) - plan slope of pipe segment; and column (8) - depth of sand and gravel sediment bed. A suspended solids waste rate of 0.5 lb/capita/day was used in the analysis. This rate was determined from an analysis of background samples taken during the flushing program. Additional sewage background sampling .s presently being conducted in the study and these results will .ater be used to sharpen the preliminary results presented here. The background sewage flow per capita determined from field measurements conducted during the flushing program ranged from 125 gpcd up to 275 gpcd. The peaking factors relating maximum daily flow to average flow were determined from field data.

Inspection of the measured results shown in column (3) with the predicted values given in column (4) indicates the deposition .odel estimates compare reasonably well with field results. n general, the model under-estimates deposition loadings and will e modified to reflect this bias in future phases of work.

TABLE C-1. PRELIMINARY OVERALL COMPARISON OF MEASURED AND PREDICTED RESULTS OF SOLIDS DEPOSITION IN TEST SEGMENTS

(1) Test Segment Location	(2)* Measured (A)	(3)** Measured (B)	(4)*** Predicted (C)	(4)*** Predicted (D)	(5) (E)	(6) (F)	(7) (G)	(8) (H)
Port Norfolk	1.33	1.47	1.37	1.1	12	247	0.00486	2
Shepton	1.41	1.24	1.1	.85	12	226	0.00345	2
Templeton	1.74	1.66	1.15	.92	15	187	0.0032	3
Walnut	1.03	0.65	.74	.40	15	136	0.0048	4

* All results including good and questionable experiments.
** Selected data: only good experiments free of wet weather impacts.
*** A waste generation rate of 0.5 lb/capita/day of suspended solids used (derived) from average of measured background sewage characteristics)
(A) Mean TSS Removal/Flush/Antecedent Day (kg/day)
(B) Mean TSS Removal/Flush/Antecedent Day (kg/day)
(C) Predicted Daily TSS Deposition Rates (kg/day - Per Capita Waste Rate = 125 gpcd
(D) Predicted Daily TSS Deposition Rates (kg/day) - 250 gpcd
(E) Pipe Size - Circular (in)
(F) Test Segment Length (ft)
(G) Pipe Slope Plan/Profile Maps
(H) Sediment (in)